

# Microquasars in the GeV-TeV era

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**ABSTRACT.** The discovery of non-thermal X-ray emission from the jets of some X-ray binaries, and especially the discovery of GeV-TeV gamma-rays in some of them, provide a clear evidence of very efficient acceleration of particles to multi-TeV energies in these systems. The observations demonstrate the richness of non-thermal phenomena in compact galactic objects containing relativistic outflows or winds produced near black holes and neutron stars. We review here some of the main observational results on the non-thermal emission from X-ray binaries as well as some of the proposed scenarios to explain the production of high-energy gamma-rays.

## 1. X-ray binaries and microquasars

X-ray binaries (XB) are binary systems containing a compact object (a neutron star or a stellar mass black hole) accreting matter from the companion star. Depending on the spectral type of the optical companion they are classified in High Mass X-ray binaries (HMXB) or Low Mass X-ray Binaries. For HMXBs the optical companion has an early type (either O or B) and mass transfer takes place via a decretion disc for Be stars, wind accretion or Roche lobe overflow. LMXBs, on the other hand, have an optical companion with spectral type later than B and mass transfer takes place through Roche lobe overflow. Up to now a total of 299 XBs have been catalogued, out of which 114 are HMXBs and 185 are LMXBs (Liu et al., 2006, 2007).

Microquasars are X-ray binaries that have relativistic jets resulting from the accretion onto the compact object. These relativistic jets can emit non-thermal radio emission through synchrotron radiation, so all radio emitting XBs (REXB) are microquasar candidates. 65 REXBs have been detected (22% of all XBs): 9 of them are HMXBs and 56 are LMXBs. The interaction of the relativistic jets with the optical companion radiation or with the interstellar medium can result in GeV-TeV emission from these sources. Below we explore the observations of a few selected microquasars that indicate the presence of accelerated non-thermal particle population susceptible to emit in the gamma-ray domain.

### 1.1. Superluminal jets: GRS 1915+105

The first clear evidence of relativistic jets in XRBs was found by Mirabel & Rodriguez (1994) through the detection of superluminal motion in the ejecta of the microquasar GRS 1915+105. It was proposed that relativistic electron population in the jet could emit above MeV energies through Inverse Compton scattering or even direct synchrotron (Atoyan & Aharonian, 1999). However, this particular source hasn't been detected yet in neither the GeV nor the TeV band (Saito et al., 2009; Szostek et al., 2009).

### 1.2. Strong radio outbursts: Cygnus X-3

Other galactic accreting sources have been studied best through their radio outbursts, as is the case of Cygnus X-3. This HMXB is formed by a Wolf Rayet star and a compact object that is thought to be a neutron star for orbit inclination angles above 60° or a black hole otherwise (Vilhu et al., 2009). Cyg X-3 shows flaring levels of up to 20 Jy, and was first detected and closely observed at this level in 1972, resulting in one of the best-known examples of expanding synchrotron emitting sources. These outbursts

can be modeled successfully as coming from particle injection in twin jets (Marti et al., 1992), which have been subsequently imaged through interferometric techniques (Martí et al., 2001; Miller-Jones et al., 2004).

Long-term multiwavelength monitoring of Cyg X-3 has revealed that strong radio flares occur only when the source shows high soft X-ray flux and a hard power-law tail. If the electrons responsible for the strong radio outbursts and the hard X-ray tails are accelerated to high enough energies, detectable emission in the  $\gamma$ -ray energy band is possible. In the last few months, both the AGILE/GRID (Tavani et al., 2009) and Fermi/LAT (Abdo et al., 2009c) collaborations have published clear detections of Cyg X-3 in high energy gamma-rays.

### 1.3. Jet-medium interaction: SS 433

For other microquasars, one of the most prominent features is the interaction between their relativistic jet and the interstellar medium surrounding them. While theoretical predictions for gamma-ray emission have been made (Bordas et al., 2009), none has been detected yet. The most notable case with this feature is SS 433, a HMXB with twin relativistic precessing jets. The precession has been clearly observed in the radio domain below arcsecond scales (Stirling et al., 2002). At a larger scale, the interaction of the jets with the surrounding parent nebula W50 has deformed the originally spherical nebula into a twisting elongated shape (Dubner et al., 1998). This source is the only one for which the jets are known to contain a hadronic component after Doppler shifted iron lines were detected in spatially resolved regions corresponding to the jet and counter-jet, proving that particle re-acceleration in relativistic jets does not only affect electron but also atomic nuclei (Migliari et al., 2002).

## 2. Detected Binary TeV sources

Among the VHE sources detected with the Čerenkov telescopes there are three clearly associated to X-ray binaries. These Binary TeV sources (BTV), PSR B1259–63 (Aharonian et al., 2005a), LS I +61 303 (Albert et al., 2006) and LS 5039 (Aharonian et al., 2005b), have a bright high-mass primary star, which provides an intense UV seed photon field for inverse Compton scattering of particles accelerated around the compact object. All of them have been detected at TeV energies in several parts of their orbits and show variable emission and hard spectrum. The emission is periodic in the systems LS 5039 and LS I +61 303, with a period of  $3.9078 \pm 0.0015$  days and  $26.8 \pm 0.2$  days respectively (Aharonian et al., 2006; Albert et al., 2009), consistent with their orbital periods (Casares et al., 2005a,b; Aragona et al., 2009). These two sources also share the distinction of being the only two known high-energy emitting X-ray binaries that are spatially coincident with sources above 100 MeV listed in the Third EGRET catalog (Hartman et al., 1999). LS 5039 is associated with 3EG J1824–1514 (Paredes et al., 2000) and LS I +61 303 with 3EG J0241+6103 (Kniffen et al., 1997). Both sources have also been detected by the Fermi observatory (Abdo et al., 2009a,b). In the case of PSR B1259–63 the periodicity has not been yet determined because the long orbital period (3.4 years) requires extensive monitoring during several years with the Čerenkov telescopes. The source was not detected by EGRET.

Another high-mass X-ray binary, Cygnus X-1, was observed with MAGIC during a short-lived flaring episode, and strong evidence ( $4.1\sigma$  post-trial significance) of TeV emission was found (Albert et al., 2007).

The nature of the compact object is well determined in only two sources. In the case of Cygnus X-1 it is a black hole and, in the case of PSR B1259–63, a neutron star. For LS I +61 303 and LS 5039 there is no strong evidence yet supporting either the black hole nor the neutron star nature of the compact objects. Some of these sources have also

been detected at MeV and GeV energies by instruments onboard the Compton Gamma-ray Observatory (CGRO), like COMPTEL and EGRET (as commented above), or by the two current spatial missions *AGILE* and *Fermi*. A common characteristic of these four sources is that all of them are radio emitters, producing non-thermal radiation. These sources, with the exception of PSR B1259–63, show elongated radio structures of synchrotron origin. It is possible that PSR B1259–63 has this kind of structure but has not yet been detected with the present sensitivity and resolution of the instruments available in the southern hemisphere.

## 2.1. PSR B1259–63

PSR B1259–63 is the first variable galactic source of VHE gamma-rays discovered. It is a binary system containing a Be main sequence donor, known as LS 2883, and a 47.7 ms radio pulsar orbiting it every 3.4 years in a very eccentric orbit with  $e = 0.87$  (Johnston et al., 1994).

The radiation mechanisms and interaction geometry in this pulsar/Be star system were studied in Tavani & Arons (1997). In a hadronic scenario, the TeV light-curve, and radio/X-ray light-curves, can be produced by the collisions of high energy protons accelerated by the pulsar wind and the circumstellar disk (Neronov & Chernyakova, 2007). A very different model is presented in Khangulyan et al. (2007), where it is shown that the TeV light curve can also be explained by IC scenarios of gamma-ray production.

## 2.2. LS I +61 303

This source is located at a distance of  $2.0 \pm 0.2$  kpc (Frail & Hjellming, 1991). It contains a rapidly rotating B0 Ve star with a stable equatorial shell, and a compact object of unknown nature with a mass between 1 and  $5 M_{\odot}$ , orbiting it every 26.5 d (Hutchings & Crampton, 1981; Casares et al., 2005a). Quasi-periodic radio outbursts monitored during 23 years have provided an accurate orbital period value of  $P_{\text{orb}} = 26.4960 \pm 0.0028$  d and the presence of a 4.4 yr superorbital periodicity in the phase location and amplitude of the outburst (Paredes, 1987; Gregory, 2002). The orbit is eccentric ( $e \simeq 0.72$ ) and periastron takes place at phase  $0.23 \pm 0.02$ , assuming  $T_0 = \text{JD } 2,443,366.775$  (Casares et al., 2005a). Grundstrom et al. (2007) obtained new orbital parameters, revealing an eccentricity of 0.55 and a periastron at phase  $0.30 \pm 0.01$ . However, the Balmer lines used in their study are possibly contaminated by the stellar wind. New radial velocities measurements reported recently by Aragona et al. (2009) give improved orbital elements for LS I +61 303 and for LS 5039.

An orbital X-ray periodicity has been found using *RXTE*/ASM archival data (Paredes et al., 1997). Simultaneous X-ray (*RXTE*/PCA) and radio observations of LS I +61 303 over the 26.5 day orbit showed a significant offset between the peak of the X-ray and radio flux. The X-ray outbursts, starting around phase 0.4 and lasting up to phase 0.6, peak almost half an orbit before the radio ones (Harrison et al. (2000) and references therein). Similar results have recently been obtained at higher energies with *INTEGRAL* data (Hermsen et al., 2006). Recently the MAGIC collaboration have detected correlated X-ray and VHE emission from LS I +61 303 during a simultaneous multi-wavelength campaign covering 60% of an orbit (Anderhub et al., 2009), suggesting that the same leptonic particle population is responsible for the emission in these two energy bands. The maximum of the radio outbursts varies between phase 0.45 and 0.95. Massi et al. (2004) reported the discovery of an extended jet-like and apparently precessing radio emitting structure at angular extensions of 10–50 milliarcseconds. VLBA images obtained during a full orbital cycle show a rotating elongated morphology (Dhawan et al., 2006), which may be consistent with a model based on the interaction between the relativistic wind of a young non-accreting pulsar and the wind of the stellar companion

(Dubus (2006); see nevertheless Romero et al. (2007) for a critical discussion of this scenario).

The gamma-ray lightcurve observed by *Fermi* and reported by Abdo et al. (2009b) shows hints of an orbit-to-orbit variability. The increase in integrated orbital flux observed during the past months could be related to the 4.4 yr superorbital periodicity. Given the similarity of the gamma-ray and radio orbital lightcurves of the source, a similar long term behavior is to be expected. The analysis of *Fermi* data during the following months will allow us to better understand the multiple components that conform the broad band SED of this peculiar source. In Fig. 1 we show the difference in the radio peak amplitude between an active phase and a quite phase of the superorbital period.

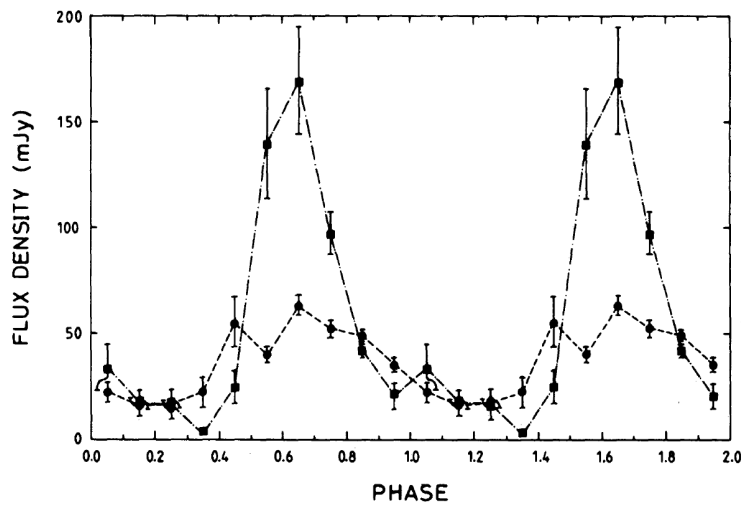


Fig. 1. Average radio lightcurves for the active phase (squares, dash-dotted) and quiet phase (circles, dashed) of the 4.4 yr superorbital period. Figure adapted from Paredes et al. (1990). It will be very interesting to explore whether this modulation is also present in the HE gamma-ray domain.

### 2.3. LS 5039

LS 5039 is a high-mass X-ray binary containing a compact object of unknown mass, 1.5–10  $M_{\odot}$  depending on the binary system inclination, which is an unknown parameter. The neutron star or black hole orbits an O6.5V((f)) star every 3.9 days in an eccentric orbit with  $e = 0.35$ , and is located at 2.5 kpc (Casares et al., 2005b). The radio emission of LS 5039 is persistent, non-thermal and variable, but no strong radio outbursts or periodic variability have been detected so far (Ribó et al., 1999, 2002). VLBA observations allowed for the detection of an elongated radio structure, interpreted as relativistic jets (Paredes et al., 2000). The discovery of this bipolar radio structure, and the fact that LS 5039 was the only source in the field of the EGRET source 3EG J1824–1514 showing X-ray and radio emission, allowed to propose the physical association of both sources (Paredes et al., 2000). A theoretical discussion of the radio properties of LS 5039 can be found in Bosch-Ramon (2009).

X-ray observations of LS 5039 with the *Suzaku* satellite, covering one and half orbits, show strong modulation over the orbital period of the system that is closely correlated with the TeV gamma-ray light curve (Takahashi et al., 2009). Furthermore, when com-

paring this lightcurve with observations taken more than ten years ago it has been found to be extremely stable over long periods Kishishita et al. (2009). The X-ray/TeV correlation seems to indicate a synchrotron origin for the X-rays, and that the electrons producing the synchrotron radiation are also responsible for the TeV emission via IC scattering. However, whereas the TeV periodicity is mainly explained by the photon-photon pair production and anisotropic IC scattering, the X-ray modulation seems to be produced by adiabatic losses dominating the synchrotron and IC losses of electrons (Takahashi et al., 2009). To avoid heavy absorption, it is required that the gamma-ray emission be produced at the periphery of the binary system (Khangulyan et al., 2008; Bosch-Ramon et al., 2008), although a scenario accounting for electromagnetic cascading has been also considered (Sierpowska-Bartosik & Torres, 2007; Khangulyan et al., 2008).

Two incompatible scenarios have been proposed to explain the acceleration mechanism that powers the relativistic electrons. In the first one electrons are accelerated in the jet of a microquasar powered by accretion (Paredes et al., 2006). In the second one they are accelerated in the shock between the relativistic wind of a young non-accreting pulsar and the wind of the stellar companion (Dubus, 2006).

#### 2.4. Cygnus X-1

Cygnus X-1 is the brightest persistent HMXB in the Galaxy, radiating a maximum X-ray luminosity of a few times  $10^{37}$  erg s<sup>-1</sup> in the 1–10 keV range. At radio wavelengths the source displays a  $\sim 15$  mJy flux density and a flat spectrum, as expected for a relativistic compact (and one-sided) jet ( $v > 0.6c$ ) during the low/hard state (Stirling et al., 2001). A transient relativistic radio jet was observed during a phase of repeated X-ray spectral transitions in an epoch with the softest 1.5–12 keV X-ray spectrum (Fender et al., 2006). Arc-minute extended radio emission around Cygnus X-1 was found using the VLA (Martí et al., 1996). Its appearance was that of an elliptical ring-like shell with Cygnus X-1 offset from the center. Later, as reported in Gallo et al. (2005), such structure was recognised as a jet-blown ring around Cygnus X-1. This ring could be the result of a strong shock that develops at the location where the pressure exerted by the collimated jet, detected at milliarcsec scales, is balanced by the ISM. The observed thermal Bremsstrahlung radiation would be produced by the ionized gas behind the bow shock.

MAGIC very high energy gamma ray observations of this source revealed strong evidence (at a  $4.1\sigma$  post-trial confidence level) for a short flaring episode from Cygnus X-1. These TeV measurements were coincident with an intense state of hard X-ray emission observed by *INTEGRAL*, although no obvious correlation between the X-ray and TeV emission was found (Malzac et al., 2008). The detection occurred around the superior conjunction of the compact object, when the highest gamma-ray opacities are expected. After computing the absorbed luminosity that is caused by pair creation for different emitter positions, it has been suggested that the TeV emitter is located at the border of the binary system (Bosch-Ramon et al., 2008). A recent study of the opacity and acceleration models for the TeV flare can explain qualitatively the observed TeV spectrum, but not its exact shape (Zdziarski et al., 2009).

#### 2.5. A new BTV candidate: HESS J0632+057

HESS J0632+057 was discovered by the HESS telescope array as a point-like source in Monoceros (Aharonian et al., 2007). Its energy spectrum is consistent with a power-law with photon index of 2.53 and flux normalisation of  $9.1 \times 10^{-13}$  cm<sup>-2</sup> s<sup>-1</sup> TeV<sup>-1</sup>. No evidence of flux variability was found. Three different sources - the *ROSAT* source 1RXS J063258.3+054857, the EGRET source 3EG J0634+0521 and the star MWC 148 - were suggested as possible associations with HESS J0632+057.

Later X-ray observations with *XMM-Newton* revealed a variable X-ray source, XMMU J063259.3+054801, which is positionally coincident with the massive B0pe spectral type star MWC 148 (HD 259440) and compatible in position with HESS J0632+05 (Hinton et al., 2009). The X-ray spectrum is hard, and can be fitted with an absorbed power-law model with a 1 keV normalization of  $(5.4 \pm 0.4) \times 10^{-5} \text{ keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ , a photon index of  $1.26 \pm 0.04$  and a column density of  $(3.1 \pm 0.3) \times 10^{21} \text{ cm}^{-2}$ . The spectral energy distribution (SED) of HESS J0632+057, assuming that the sources associated at different spectral bands are the real counterparts, looks similar to that of the TeV binaries LS I +61 303 and LS 5039.

VERITAS observed HESS J0632+057 during three different epochs obtaining no significant evidence for gamma-ray emission (Acciari et al., 2009). The HESS detection and the VERITAS non detection seems to point to a long-term gamma-ray variability. This seems to happen also in the X-ray band, when comparing the *XMM-Newton* data (Hinton et al., 2009) and *Swift* data taken contemporaneously with VERITAS (Acciari et al., 2009). The absence of radio emission in this area, based on the NRAO VLA Sky Survey (NVSS) catalog (Condon et al., 1998), seemed to indicate that any possible radio counterpart should be either faint and/or variable. This suspicion has been confirmed very recently. Radio observations carried out in 2008 with the VLA at 5 GHz and GMRT at 1280 MHz have found a faint and unresolved source at the position of MWC 148 (Skilton et al., 2009). While the radio flux density at the lower frequency is not variable, there is a significant flux variability on month timescales at 5 GHz. The TeV variability, as well as the X-ray and the radio variability clearly associated with MWC 148, gives support to the idea proposed by Hinton et al. (2009) that HESS J0632+057 is likely a new gamma-ray binary. However, further observations are necessary to determine the binarity of MWC 148.

### 3. Summary

The study of microquasars and other compact binary sources in the GeV-TeV domain in recent years has brought new insights into these sources, but probably even more unanswered questions. In the following years, with the exploitation of *Fermi* data and a new generation of Čerenkov telescopes, will hopefully bring the understanding of these sources.

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